The importance of the diurnal cycle of Aerosol Optical Depth in West Africa

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[1] High resolution atmospheric simulations with the AROME model coupled with a dust module over West Africa for the whole of June 2006 were used to calculate aerosol optical thickness (AOT). Simulations showed a significant diurnal cycle of 0.2 in the dust AOT that could not be inferred from the MODIS Deep Blue retrievals due to their timings. Dust sources are mainly driven by the breakdown of the early morning low-level jet and by moist convection in the afternoon, leading to opposite diurnal cycles. Also, simulations show that cloud cover significantly prevents the observation of AOT. The under-sampling of the diurnal cycle by satellites plus the impact of cloud masks on the space-borne AOT retrievals induce an underestimation of 0.28 (~40%) over the convective regions and an overestimation of 0.1 (17%) over morning source areas like Bodélé. A combination of observations and high-resolution models could constrain bias and give a more realistic AOT climatology. **Citation:** Kocha, C., P. Tulet, J.-P. Lafore, and C. Flamant (2013), The importance of the diurnal cycle of Aerosol Optical Depth in West Africa, *Geophys. Res. Lett.*, *40*, 785–790, doi:10.1002/grl.50143.

1. Introduction

[2] Mineral dust affects the atmospheric equilibrium of earth through its direct impact on the atmospheric radiation budget, which is due to scattering and absorption of short and long wave radiation and re-emission of long wave radiation [*Houghton et al.*, 2001], and its indirect influence on microphysical cloud processes [*Forster et al.*, 2007]. These effects of dust depend on its chemical and physical properties, concentration and spatial and temporal distribution. However, these properties exhibit great, but scarcely documented, variability. Thus dusts are one of the major sources of uncertainty in the projection of climatic changes and their interpretation [*Forster et al.*, 2007].

[3] West and North Africa are the primary sources of dust on Earth, providing 25 to 50% of the total dust mass [*Luo et al.*, 2004]. The large quantities of aerosols emitted in these regions strongly modify the vertical stability of the atmosphere and the associated atmospheric processes [e.g. *Kocha et al.*, 2012]. For these reasons, accurate distributions of dust need to be implemented in numerical weather predicting models to improve their forecasts.

[4] Satellite data on aerosol optical thickness (AOT) over large desert areas have become increasingly available. In spite of their large uncertainties compared to the scarce ground-based observations, especially over the bright arid and desert areas, satellite remote sensing data are extensively used to analyze the spatio-temporal distribution and properties of dust aerosols. However, satellite dust-related retrievals are impaired by several limitations: (i) with the notable exception of CALIOP, they cannot provide information on the vertical distribution of dust even though this has an important impact on the radiative forcing, (ii) dust detection is not possible in the presence of clouds, and (iii) the retrievals over a given area are collected at the time of the satellite overpass i.e. at most twice a day for the above mentioned instruments, generally around noon and midnight local time.

[5] Recent studies have shown that haboobs (dust fronts occurring at the leading edge of cold pools emanating from convective storms) are a non-negligible source of dust in these regions [*Knippertz et al.*, 2007; *Tulet et al.*, 2010; *Marsham et al.*, 2011] and can contribute to 50% of the dust production during June [*Marsham et al.*, 2012]. There is now evidence that space-borne retrievals underestimate the AOT over the Sahara [*Williams*, 2008] because (i) haboobs cannot always be observed below the often wide anvils of convective systems, and (ii) haboobs in West Africa generally occur in the afternoon and the evening, between the times when the most relevant satellite is passing over.

[6] On the other hand, dust distributions derived from Chemical Transport Models (CTM) still remain insufficiently precise. Because of their coarse horizontal mesh size, CTM generally underestimate small-scale dust sources. Furthermore, because CTM treat dust as tracers, they ignore any radiative impact that dust aerosols may have, on the atmospheric dynamics for instance. Also, various model configurations can induce variations of 55 to 75 % on the modeling of the dust diurnal cycle over North Africa [*Luo et al.*, 2004]. In particular, since parameterisations of moist convection are ineffective at generating cold pool outflows and propagating convective systems, models can underestimate the emission of dust on the order of 50% over West Africa [*Marsham et al.*, 2011].

[7] Hence, it appears that dust emissions associated with haboobs are underrepresented in space-based observations and inadequately taken into account by models for which convection is parameterized. For instance, the underrepresentation of haboobs is likely to strongly bias aerosol climatologies used by both global climate models (GCM) and numerical weather prediction models (NWP).

[8] The aim of this paper is to show that high-resolution models can improve the documentation of dust distribution over West Africa, particularly by reproducing the diurnal cycle of convection and surface winds more accurately. The study focuses on the month of June 2006 over West

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Africa. June is generally prone to large dust loads [*Engelstaedter and Washington*, 2007] and high occurrence of deep convection. Our results raise some questions about the accuracy of current dust climatology used in atmospheric models, which is mostly based on satellite observations or GCM simulations.

2. Data and Methodology

2.1. Observations

[9] The regional distribution of dust aerosols (mobilization and transport) was described using AOTs obtained from the MODIS/AQUA and MODIS/TERRA Deep Blue Collection 005 over desert surfaces. We used the gridded daily level 3 AOD product at 550 nm (1° x 1°) processed with the Deep Blue algorithm [*Hsu et al.*, 2004] available from the Giovanni Web portal (http://disc.sci.gsfc.nasa.gov/giovanni). TERRA and AQUA orbit the Earth on heliosynchronous platforms that cross the equator at 1030 and 1330 local time, respectively. Comparisons between the Deep Blue and AERONET AODs are generally within 20–30% of each other, as demonstrated by *Salustro et al.* [2009] using AQUA collection 5.1 data from July 2002 to December 2008 over the Sahara and the Arabian Peninsula. The 1° x 1° pixels affected by clouds for more than 80% of the time and those for which the AOT standard deviation was greater than 2.5 were removed before computing the monthly mean for June 2006.

2.2. Model

[10] The new high-resolution NWP regional model AROME [*Seity et al.*, 2011] was used to simulate dust distribution over West Africa. This non-hydrostatic regional model was coupled with the Dust Entrainment and Deposition (DEAD) model [*Zender et al.*, 2003; *Grini et al.*, 2006], which calculates dust fluxes from wind friction speeds [*Marticorena and Bergametti*, 1995], and with the lognormal aerosol model ORILAM [*Tulet et al.*, 2005]. ORILAM represents the transport and the wet and dry deposition of three lognormal modes representing the fine, accumulation and coarse modes of desert dusts, which are derived from AMMA measurements [*Crumeyrolle et al.*, 2011]. The refractive index of the dust aerosols was derived from AERONET [*Dubovik and King*, 2000]. ORILAM calculates the radiative dust properties (extinction coefficient, asymmetry factor and single scattering albedo) coupled on-line with the ECMWF 2004 radiation scheme. More details and references are provided in *Kocha et al.* [2012]. The high resolution permit deep convection to be explicitly resolved and the dust lifting, transport and deposit to be correctly represented.

[11] From 1 to 30 June 2006, a total of seven 6-day forecasts were performed over a large domain [6.5°–30°N; 3°W–33°E] (outlined in Figure 1) covering most of the West African main dust sources . The simulations were made using a horizontal mesh size of 5 km with 41 levels in the vertical direction, and a time step of 60 s. Except for dust, initial and coupling fields were provided by the operational large-scale ARPEGE-Tropique model analyses. The dust-related initial fields were set near to zero on the 1 June 2006 and after were conserved from one simulation to the next.

[12] For all of the 6-day forecasts performed for June 2006, *Kocha* [2011] has shown that, after the first day of simulation (corresponding to the spin up time of the model), no model drift is detected for the following 5 days (i.e. from Day 2 to Day 6 for each forecast). The present study used Day 2 to Day 5 of each forecast to cover the entire month of June.

[13] The AROME-derived and MODIS-derived AOTs have been compared with level 2.0 AOTs retrievals from 3 AERONET stations. The AERONET observations [*Dubovik and King*, 2000] from Tamanrasset (Algeria), Banizoumbou (Mali) and Ouagadougou (Burkina-Faso) were used. Details on these comparisons are given as supplementary material. For the entire month of June 2006, 123 direct comparisons between MODIS, AERONET and AROME could be used to statistical purposes. From this, we find that good agreement between the space-borne, ground-based AOT retrievals and modeled AOTs in the range [0.5, 2] and a good agreement between ground-based and modeled AOTs in the range

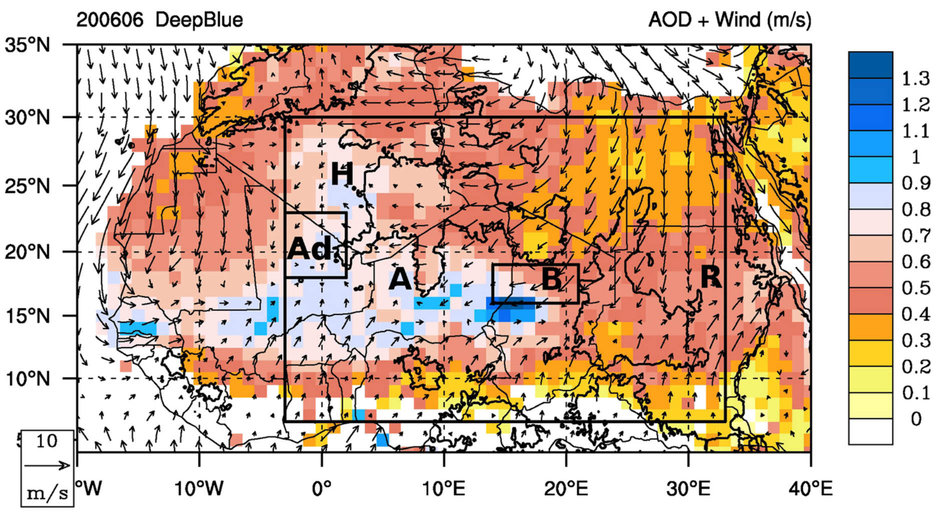

Figure 1. AOT from Deep Blue (Terra and Aqua satellites, color) and 10-m winds (arrows) from European Centre for Medium-range Weather Forecasts AMMA Reanalysis. Values are averaged for the month of June 2006. Letters refer to outstanding dust source areas in the vicinity of topographic or geographical features: “H” is Hoggar, “Ad” is Adrar des Iforas, “A” is Aïr, “B” is Bodélé, and “R” is for the Red Sea Mountains. The two boxes around “Ad” and “B” indicate the area for which the AOT evolution shown in Figure 3 was computed.

[0.2, 3]. Furthermore, the mean AOT bias of AROME against AERONET is −0.22 while the correlation coefficient is 0.76 and the regression slope is 0.71. The mean AOT bias for MODIS against AERONET is −0.13 with a correlation is 0.82 and a regression slope of 0.53. The ability of the model to reproduce the dust life cycle was also evaluated on the dust storm of March 2006 [*Kocha et al.*, 2012] and for each day of June 2006, showing good agreement with observations from 7 AERONET stations and with Deep Blue daily mean AOTs [*Kocha*, 2011].

3. Results

[14] The spatial distribution of the AOT monthly mean from the Deep Blue product (Figure 1) showed 4 main zones of strong AOT (in excess of 0.8): the Bodélé Depression, the Aïr foothills, and the areas to the west of the Adrar des Ifoghas and Hoggar Mountains (labeled **B**, **A**, **Ad**, and **H** in Figure 1 respectively) but also the South West of the Mali and Senegal. There was also a weaker dust hotspot west of the Red Sea Mountains (labeled **R**). These AOT maxima correspond to frequent observations of dust occurrence in this period [*Engelstaedter and Washington*, 2007; *Schepanski et al.*, 2007, among others].

[15] Figure 2a shows the monthly AOT from AROME averaged using 3-hourly fields from 0000 to 1800 UTC. The model reproduces a pattern of AOT in excess of 0.8 that is similar to MODIS, and highlights the AOT maxima previously spotted in the MODIS data. However, some differences between the two AOT fields can be noted (Figure 2b). The first one evidences smaller simulated AOTs than those observed with Deep Blue in a region covering the Bodélé Depression and extending south of 15°N and east of 10°E. The lack of dust to the East could be partly due to the lack of dust inflow from the Arabian Peninsula sources in the AROME simulation. The absence of aerosols other than dust (e.g. biomass-burning aerosols) in the simulation could explain the underestimation of the simulated AOT to the south. An excess of scavenging by precipitation in the intertropical convergence zone could also explain the lower AOT values in the AROME simulation in this region.

[16] In contrast, the simulated AOT was stronger than that retrieved by Deep Blue around mountainous areas such as the Western flanks of the Hoggar, the Adrar des Iforas and the Aïr. The dust detected by the brightness temperature difference from SEVERI suggests a higher occurrence of haboobs in these mountainous areas than over the Bodélé between June and August [*Schepanski et al.*, 2007]. This is consistent with the study by *Mbourou et al.* [1997] who have shown that, over the Western Sahara, the observed horizontal visibility in Timbuktu (16°43'N; 03°00'W), Hassi Messaoud (31°40'N; 06°09'E) and Zouerate (22°41'N; 12°42'W) has a strong diurnal cycle attributable to convection with the highest frequency (~53 days/year) of visibility reaching less than 5 km around 1500 UTC and the lowest frequency (~22 days/year) around 0600 UTC.

[17] The above observations support the idea that the AOT monthly mean from Deep Blue could be underestimated over the western part of the Sahara. To understand the differences between satellite retrievals and simulations, we now focus on two areas showing both high dust content in the Deep Blue (AOT ~ 0.8) and the highest differences between satellite retrievals and simulations. These areas are outlined as boxes in Figures 1 and 2, i.e. the Adrar [18–23 N; 3 W–2E] and Bodélé [16–19 N; 14E–21E] boxes. Bodélé is recognized as the greatest dust source on Earth [*Washington et al.*, 2006]. Figure 3a shows the monthly mean of the diurnal cycle of the AOT over these two boxes. Deep Blue mean retrievals are represented by 2 black filled circles for the Adrar box and 2 white squares for the Bodélé box. The two data points in each box correspond to the TERRA (0930 UTC) and AQUA (1230 UTC) overpasses. The amplitude of the diurnal fluctuations of AOT is large, being about 0.2 (peak to peak) at both locations. The most striking feature is the phase opposition of the diurnal cycle between the two regions: the AOT is maximum at 1200 UTC over Bodélé while it is maximum at 22UTC over the Adrar region.

3.1. Dynamical processes driving the AOT diurnal cycle

[18] These opposite diurnal cycles are due to the different processes leading to the uprising of dust. In the following, we shall analyze these processes based on two variables related to atmospheric dynamics known to control dust emission. The first variable considered here is the surface wind (hereafter10-m wind speed). The second one is the wind gusts computed from the 10-m wind speed.

[19] Figure 3b shows the monthly mean diurnal cycle of the 10-m wind speed over the two boxes (dashed lines). The Bodélé area shows a strong diurnal cycle with an increase of the mean 10-m wind during the morning with a peak of 7 m s-1 at 0900 UTC. Over this region, the increase of surface winds is caused by the downward mixing of the

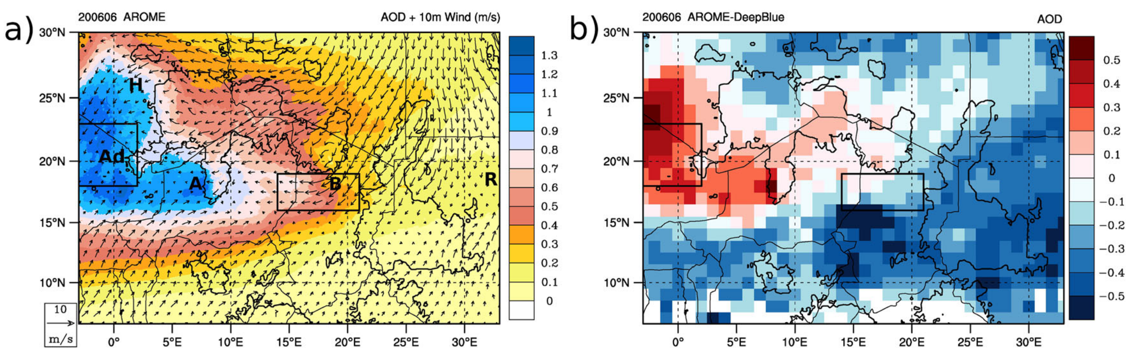

Figure 2. (a) AOT (color) and 10-m winds (arrows) from the AROME model. (b) Difference of AOT between the AROME simulation and the Deep Blue observations. Values are averaged for the month of June 2006. The meaning of letters and boxes are the same as in Figure 1.

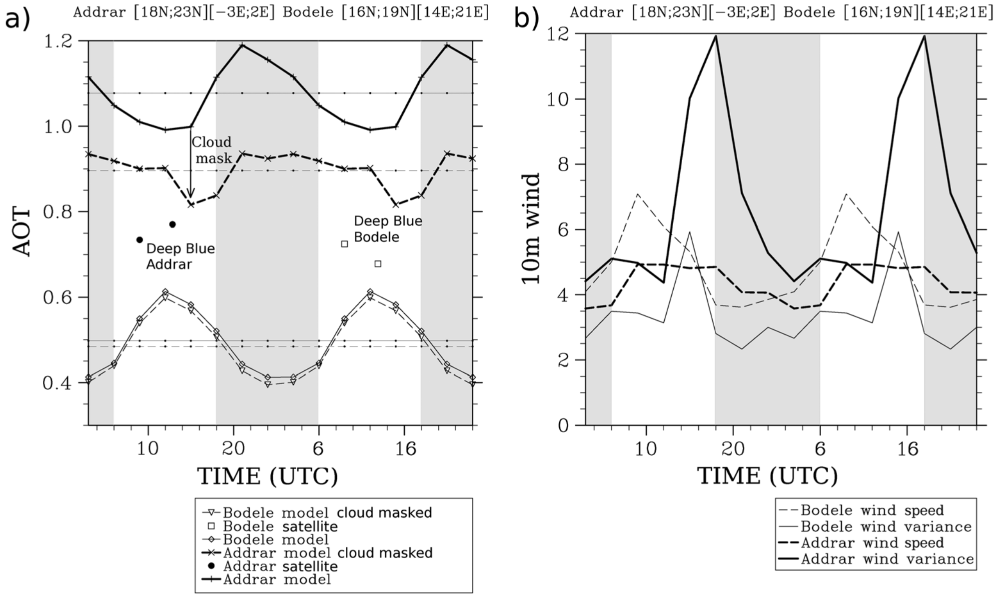

Figure 3. Composite diurnal cycle averaged over June 2006 and plotted over 48 h for the Bodélé box [16–19°N;14–21°E] and the Adrar box [18–23°N; 3°W–2°E] of (a) the AOT simulated by AROME (solid and dashed lines) and observed by Deep Blue (black points and white squares) and (b) the 10-m wind speed ($m\,s^{-1}$) (dashed lines) and the 10-m wind speed variance ($m^2\,s^{-2}$) over 1° x 1° boxes (solid lines) simulated by AROME. Values are averaged on the month of June 2006. Solid lines in (a) were computed using all AOT values. Dashed lines in (a) were computed using the cloud screened AOTs only. Light grey shaded periods correspond to nighttime. The horizontal lines in (a) correspond to mean AOT values averaged over the diurnal cycle.

low level jet after sunrise due to turbulent mixing [*Washington et al.*, 2006]. The 10-m wind speed reaches a maximum shortly before the maximum of dust-related AOT in the Bodélé box as winds are sufficiently strong to generate dust uplifts (Figure 3a).

[20] As opposed to what is observed in Bodélé, the 10-m mean wind speed over the Adrar area does not show a strong diurnal cycle (Figure 3b). It is minimum ($3\,m\,s^{-1}$) at the end of the night and maximum ($5\,m\,s^{-1}$) during the day, values that are generally considered to be too low to efficiently lift dust. However, the mean variance of the 10-m wind speed within 1° x 1° pixels over the Adrar box shows a maximum of $12\,m^2\,s^{-2}$ at 1800 UTC (Figure 3b). In this region and at this time, the main process that can induce such wind variance is the gustiness associated with the density currents emanating from convective systems. The mountainous region on the eastern side of the Adrar box is favorable for the development of deep convection with cold-pools propagating away from the convective core into the area covered by the Adrar box. In this region, long-lived, fast moving density currents are often observed due to the evaporation of hydrometeors before they reach the ground. *Kocha* [2011] has diagnosed the occurrence of density currents by using the variance of the 10-m wind speed, 2-m humidity and 2-m temperatures inside 1° x 1° boxes. The fact that the large 10-m wind speed variance values are seen between 1500 and 1800 UTC in Figure 3b strongly suggests that the maximum of variance is related to density currents (or cold pools), and hence convection. Furthermore, the maximum of AOT in the Adrar box is seen at 2200 UTC, i.e. after the density currents have entered the region, and is consistent with the propagation of haboobs. Over Bodélé, the wind variance shows a weak maximum [at 15 UTC] of $6\,m^2\,s^{-2}$ related to the gustiness of haboobs produced by afternoon convection in the area, that may also contribute to dust uplift.

[21] This analysis suggests that the out-of-phase diurnal cycles of dust-related AOT in the two regions result from the different dynamical processes at play for dust uplift: the breakdown of the low-level jet in the morning is mainly responsible for dust emission over Bodélé while haboobs related to deep convection occurring in late afternoon are responsible for dust emissions over the Adrar area.

3.2. Assessment of AOT biases in dust climatologies based upon MODIS

[22] As AQUA and TERRA pass over the region between 0930 and 1230 UTC, they capture the maximum of dust concentration over the Bodélé box (AOT ~ 0.7). Assuming that AROME correctly simulates the AOT diurnal cycle (amplitude of 0.2), AOT values based on MODIS retrievals cannot be considered as representative of a daily mean value in the region of Bodélé (as is generally assumed in dust AOT climatologies). A MODIS AOT monthly mean corrected by the simulated diurnal cycle would be around 0.6. Hence the overestimation of a MODIS monthly mean product is of the order of 0.1, i.e. 17%, due to the underrepresentation of the diurnal cycle of dust. Besides, the model shows an underestimation of the dust load maximum of 0.1. This underestimation can be due to the rather coarse vertical resolution which leads to an underestimation of the low-level jet strength and, in turn, a diminution of the surface winds (responsible for the dust uplift) as the low-level jet breaks down after sunrise [*Todd et al.*, 2008; *Johnson et al.*, 2011]. It may also be that the soil granulometry in that region is not well represented, thereby making the 17% discussed above a conservative estimate. Overall, the effect of the limited sampling of the satellite explains

~0.1 of the 0.2 AOT offset between Deep Blue and model mean AOTs for the Bodele (i.e. 50%).

[23] Similarly, the two satellites capture the minimum of dust AOT over the Adrar box (0.75) while the diurnal cycle amplitude simulated is 0.2. A MODIS AOT monthly mean corrected by the simulated diurnal cycle would be around 0.85. Hence the underestimation of a MODIS monthly mean product is of the order of 0.1, i.e. 11% due to the underrepresentation of the diurnal cycle of dust.

[24] Finally, cloudiness may also introduce biases in the AOT satellite retrievals. To quantify this bias, we derived a cloud mask from the simulated cloud fields to compute AOT only in cloud-free areas. The resulting AOT diurnal cycle is plotted in dashed lines on Figure 3a. Over Bodélé, where few clouds are generally observed, the cloud mask causes a slight decrease of the AOT, of less than 0.02 throughout the day. Cloudiness in the Adrar box is seen to be present throughout the diurnal cycle and to affect AOT retrievals substantially, leading to a mean reduction of the AOT of 0.2, and to a modification of the diurnal cycle. There is no longer a well marked maximum in AOT associated with the convection because high clouds (anvils for convective systems) screen out the dust in the low levels. Hence the underestimation of the AOT monthly mean product of MODIS can reach 0.175, i.e. 28% due to the cloud cover, in addition to the 17% from the limited temporal sampling. However, the model overestimates the AOT maxima by nearly 0.1 with respect to MODIS. This could be due to too strong density currents developing in this region leading to an overestimation of the dust emissions caused by too strong surface winds. Overall, the effect of the limited sampling of the satellite and cloud cover explains ~0.17 of the 0.3 AOT offset between Deep Blue and model mean AOTs for Adrar (i.e. 66%).

4. Summary and conclusion

[25] Commonly available AOT climatologies are generally based on polar-orbiting satellites with wide-field-of-view instruments on board that provide the highest possible horizontal resolution as well as the best coverage on a daily basis. However, high resolution simulations of dust emission and subsequent transport and scavenging with AROME performed for the whole month of June 2006 evidenced discrepancies up to 0.3 between the observations and the AOT fields output by the model.

[26] Visibility observations and simulations showed that there was a significant diurnal cycle in the dust AOT that could not be inferred from the MODIS retrievals due to their limited sampling of the diurnal cycle. This diurnal cycle was mainly driven by the breakdown of the early morning low-level jet over Bodélé, while it was driven by the diurnal cycle of moist convection over the Adrar region, leading to AOT maxima at 1200 UTC and 2100 UTC respectively. AQUA and TERRA pass over the Bodélé region at the time when the daily dust emission is maximum whereas they capture the daily minimum of emission in the Adrar region. A major limitation of space-borne retrievals is also linked to the monitoring of dust in the presence of clouds. Cloud cover is likely to impact the AOT diurnal cycle significantly in the Adrar convective region. According to the model, taken together, the undersampling of the diurnal cycle by satellites and masking by cloud could result in an underestimation of the mean AOT by 0.275 (~40%) for the Adrar region and an overestimation of 0.1 (17%) for the Bodélé area, known to be the "Mother of all sources". This explains around 60% of the discrepancies between high resolution simulations and satellite AOT estimates. If a correction would be applied to the June AOT climatology from MODIS, it would lead to similar AOTs (~0.8) over Bodélé and the region west of the Hoggar. Other satellite AOT retrievals as inferred from the Multi-angle Imaging Spectro-Radiometer (MISR) and the Ozone Monitoring Instrument (OMI) likely present the same problems than MODIS product as they overpass times are the same (0930 and 1230UTC respectively).

[27] Also, based on this study and other [*Marsham et al.*, 2011; *Reinfried et al.*, 2009], it can be assessed that non-convection-permitting models that do not explicitly resolve convection will probably underestimate dust emissions due to density currents in West and North Africa (even if they have a built-in dust module). Today, the reliability of parameterizations and the increased computational capabilities of newly available high-resolution models give a better representation of the processes involved in dust formation and transport at the relevant scales. They can provide another quite realistic and complementary way to estimate the distribution of aerosols. Here, we stress that the diurnal cycle of dust concentration over West Africa is pronounced. Because dusts have a significant radiative forcing that can impact meteorological forecasts, the dust fields from both NWP and climate models need to be assessed against a realistic AOT climatology. We propose a combination of observations and convection-permitting models here to constrain bias and build a more realistic AOT climatology.

[28] **Acknowledgements.** MODIS deep blue aerosol optical depth used in this study were produced with the Giovanni online data system, developed and maintained by the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC). We thank the AERONET site managers. We thank J. Marsham for his advises on how to improve the manuscript.

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